Renewable and Sustainable Energy Reviews 14 (2010) 430–437

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Climate change impacts on wind energy: A review

S.C. Pryor *, R.J. Barthelmie

Atmospheric Science Program, College of Arts and Sciences, Indiana University, 701 E Kirkwood Avenue, Bloomington, IN 47405, USA

ARTICLE INFO

Article history:
Received 1 June 2009
Accepted 14 July 2009

Keywords:
Climate non-stationarity
Wind resources
Extreme wind speeds
Icing
Sea icing
External conditions

ABSTRACT

Expansion of wind energy installed capacity is poised to play a key role in climate change mitigation. However, wind energy is also susceptible to global climate change. Some changes associated with climate evolution will likely benefit the wind energy industry while other changes may negatively impact wind energy developments, with such 'gains and losses' depending on the region under consideration. Herein we review possible mechanisms by which global climate variability and change may influence the wind energy resource and operating conditions, summarize some of the tools that are being employed to quantify these effects and the sources of uncertainty in making such projections, and discuss results of studies conducted to date. We present illustrative examples of research from northern Europe. Climate change analyses conducted for this region, which has shown considerable penetration of wind energy, imply that in the near-term (i.e. to the middle of the current century) natural variability exceeds the climate change signal in the wind energy resource and extreme wind speeds, but there will likely be a decline in icing frequency and sea ice both of which will tend to benefit the wind energy industry. By the end of the twenty-first century there is evidence for small magnitude changes in the wind resource (though the sign of the change remains uncertain), for increases in extreme wind speeds, and continued declines in sea ice and icing frequencies. Thus the current state-of-the-art suggests no detectable change in the wind resource or other external conditions that could jeopardize the continued exploitation of wind energy in northern Europe, though further research is needed to provide greater confidence in these projections.

Contents

1. Introduction . . . 430
2. Impact of climate change on the wind resource . . . 432
   2.1. Wind resource magnitude . . . 432
   2.2. Variability of the wind resource. . . . 433
3. Impact on operation and maintenance of wind farms and turbine design . . . 434
   3.1. Extreme wind speeds and gusts. . . . 434
   3.2. Icing. . . . 434
   3.3. Sea ice and permafrost . . . 435
   3.4. Other factors . . . 435
4. Concluding remarks. . . . 436
   Acknowledgements . . . 436
   References . . . 436

1. Introduction

Renewable energy sources currently meet approximately 14% of energy demand world-wide [1,2], and are poised to play an even greater role in future energy provision [3]. These technologies provide a key component of efforts to mitigate climate change [1,4], and can contribute to the security of energy supply and environmental protection measures [5,6].

Of the renewable energy technologies applied to electricity generation, wind energy ranks second only to hydroelectric in terms of installed capacity and is experiencing rapid growth. The European Union has set a binding target of a 20% renewable energy

* Corresponding author. Tel.: +1 812 855 5155; fax: +1 812 855 1661.
E-mail address: spryor@indiana.edu (S.C. Pryor).

1364-0321/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2009.07.028

contribution by 2020, which equates to 34% of electricity production. It is estimated that wind energy could contribute one-third of this production [7]. Wind-generated electricity contributed over 1% of global demand for the first time in 2007, when installed capacity grew to 94 GW [8]. In 2008, a further 27 GW of capacity was commissioned and capacity increased 29% to nearly 121 GW [9]. It has been suggested that installed capacity will increase fivefold over the next 10-year period, to exceed 700 GW by 2017 [10], which is possible at current growth rates. Wind energy is market-ready in that the technology is mature and the price of power is broadly competitive to other types of new generation, depending on the location [11]. In terms of energy and carbon balance, about 3–7 months of turbine operation are required to recover the energy spent in the full life cycle of the turbine (including removal and disposal) and avoided emissions range from 391 to 828 g of carbon dioxide per kWh [12].

Wind energy, like many of the renewable technologies, is also susceptible to climate change because the ‘fuel’ is related to the global energy balance and resulting atmospheric motion [13]. Hence here we seek to ‘close the loop’ by asking the question; ‘what impact might global climate change have on the wind energy industry?’

Atmospheric conditions enter into the design and operation of wind turbines and wind farms largely under the rubric of ‘external conditions’. The wind climate governs the energy density in the wind and hence the power that can potentially be harnessed:

$$E = \frac{1}{2}\rho U^3 \tag{1}$$

where

E = energy density (W m^{-2}),
ρ = air density (kg m^{-3}),
U = wind speed at hub-height (m s^{-1}).

Assuming the time series of wind speeds conforms to a two-parameter Weibull distribution as is common in most high-wind speed environments [14]:

$$P(U) = 1 - \exp\left[-\left(\frac{U}{A}\right)^k\right] \tag{2}$$

where

A = Weibull scale parameter (m s^{-1}),
k = Weibull shape parameter.

E can also be determined from:

$$E = \frac{1}{2}\rho A^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{3}$$

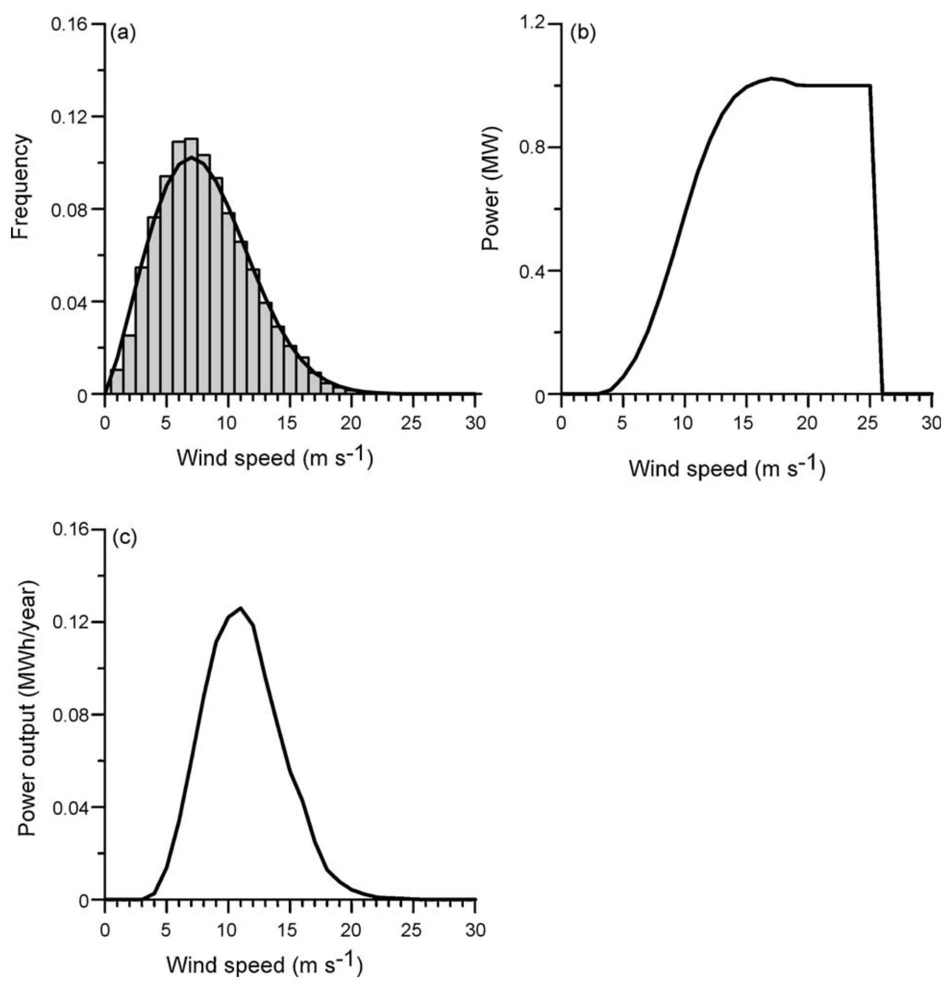

Fig. 1. (a) Frequency distribution of wind speeds with the filled bars showing observations from a Danish coastal site for the period 1997–2003. The mean wind speed at 50 m height at the site is 8.1 m s^{-1}. The line shows the fitted Weibull distribution where the Weibull scale factor A (related to the central tendency) is 9.1 m s^{-1} and the shape factor k (related to the variability) is 2.25. (b) A standard power curve for a wind turbine rated at 1 MW. (c) The power output as a function of wind speed for the wind climate and wind turbine shown above.

where

Γ = gamma function.

Given the energy in the wind is the cube of wind speed (Eq. (1)), a small change in the wind climate can have substantial consequences for the wind energy resource. For a change in wind speed at turbine hub-height of 0.5 m s^{-1}, from 5 to 5.5 m s^{-1} (i.e. a 10% change), the energy density increases by over 30%. It is also clear that the wind resource is largely dictated by the upper percentiles of the wind speed distribution (Fig. 1), a factor that is further amplified by the non-linear relationship between incident wind speed and power production from a wind turbine (i.e. the wind turbine power curve, Fig. 1).

The wind climate also governs aspects of the wind turbine design, via its governing role in wind turbine loading through, for example, turbulence intensity, wind shear across the turbine blades, and transient wind conditions such as the occurrence of extreme wind speeds and directional changes [15]. Other atmospheric conditions that are of importance to the design, operation or power production from wind turbines include operational temperatures, air density, icing and corrosion and abrasion due to airborne particles [15]. Herein we review possible mechanisms by which global climate variability and change may influence the wind energy industry via changes in these and other key parameters, summarize some of the tools that are being employed to quantify these effects, discuss results of studies conducted to date, and show illustrative examples of research from northern Europe.

2. Impact of climate change on the wind resource

2.1. Wind resource magnitude

The principal and most direct mechanism by which global climate change may impact the wind energy industry is by changing the geographic distribution and/or the inter- and intra-annual variability of the wind resource. Research undertaken to quantify this effect generally relies on application of downscaling methodologies designed to extract higher resolution projections of climate parameters of interest from coupled Atmosphere-Ocean General Circulation Models (AOGCMs, also referred to as Global Climate Models (GCMs)). These approaches can be broadly classified into dynamical (application of Regional Climate Models (RCMs)) or statistical (development of empirical transfer functions between aspects of the large-scale climate and local climate variables) downscaling.

Dynamical downscaling is conducted using limited area models—RCMs that use the same or similar numerical schemes and parameterizations to those employed in GCMs but that are run with higher resolution over a target region of interest. GCMs have typical spatial resolution below $0.5 \times 0.5^{\circ}$, while RCMs are run at or above this spatial discretization (e.g. in the NARCCAP project in the USA [16], and the PRUDENCE [17] and ENSEMBLES [18,19] projects in Europe). Dynamical downscaling using RCMs is theoretically preferable to statistical (empirical) downscaling, and can be conducted for any location regardless of the availability of observations of the surface variable. However, even dynamical downscaling is not completely based on first principles, but employs parameterizations to represent unresolved processes (e.g. sub-grid scale processes). Thus although RCM can, in principle, respond in physically consistent ways to external conditions not realized in the training period, empirical constants used in these parameterizations are based on observations in domains in which the models were developed and may not be fully transferable to other climate regimes [20]. Although RCMs resolve terrain and coastlines better than GCMs they are dependent on the quality of lateral boundary information provided by the GCMs in which they are nested. They produce higher spatial variability over complex topographic features and may be of particular utility where high spatial variability results from fine-scale dynamical processes, such as mesoscale circulations.

Simulation of near-surface wind climates and energy density represents a severe challenge to GCMs and RCMs. Due in part to the spatial scales of wind speed variability, RCMs do not fully reproduce contemporary wind climates [21–23] or historical trends [24], and the model-to-model variability is of comparable magnitude to the climate change signal present in future simulations [25–27]. To overcome issues of sub-grid scale variability and truncation of the wind speed probability distribution that characterize many RCMs, gust parameterizations have been implemented [22] and the results used to increase wind speeds in a post-processing step [23].

Sensitivity analyses conducted using the Atmosphere-Ocean Coupled Rossby Centre RCM (RCAO, version 2) indicated wind speed and energy density projections under climate change scenarios show little variability with the SRES emission scenario [28], but a high degree of sensitivity to the lateral boundary conditions (i.e. nesting GCM) [27].

Statistical downscaling is based on development of transfer functions that relate descriptors of the large-scale climate from GCMs to the local variable of interest. They thus use information from GCMs at the scales at which they show greatest skill [29], but deriving realistic scenarios and robust transfer functions is reliant on strong and stationary relationships between predictors and predictands which may not be valid in an evolving climate. Statistical downscaling may be undertaken without requiring additional data such as surface orographic and roughness maps, but requires in situ data for transfer function development. A further major advantage of statistical downscaling is that the associated computational costs are generally modest allowing for downscaling of multiple GCMs.

Traditionally a major challenge to statistical downscaling has been under-estimation of variability which is a major limitation in applications to wind speeds and energy density, where the full probability distribution is required. Two approaches have typically been applied to address this issue: inflation where the simulated variability is increased by multiplication by a specified factor (in some instances using techniques which ensure the correct resultant variability), and randomization where noise (often derived from the synoptic scale) is added to increase the variability [30]. However, a new technique has been developed that does not require this type of adjustment [31,32]. In this technique the Weibull A and k of the wind speed distribution at a given location are directly downscaled (i.e. are the predictands) from sea-level pressure and vorticity (i.e. predictors drawn from GCM simulations). Application of this technique to northern Europe showed a high degree of skill in reproducing independent data (e.g. the mean and 90th percentile wind speeds, and energy density) during the historical period [33]. Application of the technique to output from ten GCMs resolved that stochastic influences within individual GCM simulations had only a small influence on the wind climate projections, but a major source of uncertainty in wind climate projections derived from differences in predictors (i.e. descriptors of the large-scale flow) drawn from multiple GCMs [33]. This finding is thus in accord with the results of analyses descried above conducted using a RCM which also illustrated the key role of the nesting GCM in dictating the climate sensitivity of wind regimes.

Despite the caveats given above, some generalizations may be drawn from research applying downscaling in the context of wind speeds and energy density over Europe. By the end of the twenty-

first century there may be an increase in wintertime energy density in the north [27] and a decline in southeast [34]. This also appears to be true for annual mean wind speeds [35]. This finding is consistent with a continued tendency toward the positive phase of the North Atlantic Oscillation [36], which is known to be a strong determinant of winter wind speeds in northern Europe [37], and poleward displacement of storm tracks [29]. When the new probabilistic empirical downscaling approach based on downscaling of the Weibull distribution parameters was applied to stations in northern Europe using a suite of GCMs the results indicate an absence of significant changes in wind energy density to the middle of the twenty-first century, and that changes by the end of the century in the mean and 90th percentile wind speeds and energy density (Fig. 2a) are small ($<\pm10\%$) and comparable to the current variability manifest in downscaling from different AOGCMs [26], and natural variability within the climate system.

Empirical downscaling for the USA using linear techniques applied to output from two AOGCMs suggested modest declines ($<3\%$) in mean wind speeds in the next 50 years, and less than 5% over the next 100 years [38]. Research conducted in the northwest states of the USA using classification and regression trees methods in the transfer functions also indicate a decline in wind energy density during the summer, but little or no change in the winter under two climate change emission scenarios and output from four AOGCMs [39].

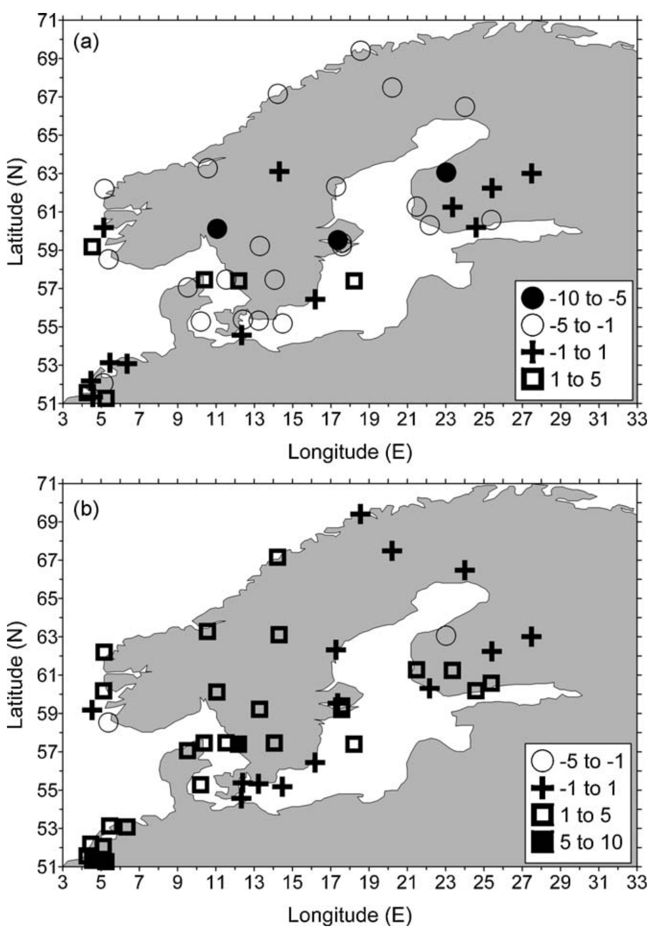

Fig. 2. Ensemble average difference in percent of (a) energy density and (b) 50-year return period wind speed computed using a probabilistic empirical downscaling approach [26] for 43 stations across northern Europe based on output from 8-GCMs (BCCR-BCM2.0, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Russell, IPSL-CM4, and MRI-CGCM2.3.2.). The future time period is 2081–2100, while the historical period in 1961–1990. A positive value indicates higher energy density or extreme wind in the later time period.

Brazil has a large wind resource, which was shown to substantially decline by 2100 under A2 and B2 SRES climate trajectories in an analysis using the PRECIS model [40]. The magnitude of the changes (a decline of up to 60% in the national resource), greatly exceeds changes reported for other regions of the world, and may derive partly from the simplifying assumptions employed in the study. The results can be contrasted with those from the west coast of South America which used direct output from 15 GCMs and the PRECIS model nested within HadAM3 to show large increases in near-surface winds (up to +15% in the mean wind speed) under both the A2 and B2 SRES emission scenarios [41].

2.2. Variability of the wind resource

Variability in wind speeds and energy density are inherent across a range of temporal scales, and in the context of the wind energy industry is often quantified using wind indices [42]:

$$WI = \overline{\sum_{j=1}^{n} \frac{U_j^3}{U_{i\ldots k}^3}} \times 100 \tag{4}$$

where

$j = 1, n$ indicates the time series from the period of interest,
$i \ldots k$ indicates the normalization period.

The inter- (and intra-) annual variability of wind speeds, wind indices and energy density are naturally a function of the regional climate, and frequency and intensity of transient storm systems, and the spatial scale of aggregation. At short time scales this variability leads to variable output of electricity production [12] and the need for short-term prediction [43,44]. At longer time scales (seasonal and beyond) it has relevance for coupling of production to demand, reliability of electricity production and project economics. Given the high capital costs of most renewable energy systems relative to operation and maintenance and discounting of future revenues [11], inter-annual variability can play a key role in dictating economic feasibility, hence 'The importance of a good wind year to start on when building a wind farm' [45].

Historical inter-annual variability across much of Europe, measured as the standard deviation of annual wind indices, is approximately ±10–15% [42,46] and variability from decade-to-decade has been estimated as approximately $\pm30\%$ [46]. Inter-annual variability of station specific annual mean wind speeds in Minnesota was reported as approximately $\pm5\%$ [47], which is consistent with results from northern Europe when scaled to represent energy density. Inter-annual variability of mean wind speeds over much of Europe is characterized by a normal distribution with a standard deviation of 6% [12] which is consistent with the analyses of energy density described above. In the Pacific Northwest of the USA, the standard deviation of annual mean wind speed at three individual sites varied between 4 and 10% of the mean, and the standard deviation of annual energy density was approximately 13% of the mean, while the absolute range over a 12-year period was -26 to +19% [48]. Similar findings were reported for a site in North Dakota [49]. Analyses of observational data from the Mediterranean found much higher inter-annual variability than characterizes the USA and northern Europe, and one study from an island in the eastern Mediterranean reported a standard deviation of annual mean wind speed of over 66% of the average annual mean [50].

Little research has been conducted to indicate if the inter-annual and inter-decadal variability of wind speeds and energy density will increase or decrease under climate change scenarios. In light of evidence of changing storm tracks [29] it seems probable that at

least in some locations a change in inter- and intra-annual variability of the wind resource is likely, although one study of European wind indices based on output from a single GCM found no evidence of substantial changes in the intra- or inter-annual variability during the twenty-first century [42]. Further few studies have sought to determine if our current generation models can replicate historical variability. One analysis based on output from two RCMs (MM5 and RSM) indicated a decline in inter-annual variability of grid-cell annual mean wind speeds over most of the contiguous USA during the historical period (1979–2004) irrespective of the direction of change in the annual mean wind speed from that grid cell, which may indicate decoupling of changes in the mean wind climate and variability at least in these RCM simulations [24].

3. Impact on operation and maintenance of wind farms and turbine design

Climate change may also alter not only the wind resource, but also the environmental context, operation and maintenance and/or design of wind developments. A major issue in design of wind turbines and wind farms is to characterize wind turbine loads which affect the performance and lifetime of the turbines [51]. Loads relating to external conditions can be divided into extreme loads which arise mainly from extreme (i.e. inherently rare) events with return periods of 1–50 years and fatigue loads [52] which are primarily determined by the mean wind speed and the standard deviation of wind speed fluctuations that are strongly related to site turbulence levels [53]. Because of the complexity of interactions between wind turbines and turbine components with external conditions, structural dynamic models are used to assess loads based on a number of frequently updated design load cases [15,52,54,55]. We are not aware of any study that has sought to quantify possible changes in the parameters used in the design load cases in the context of climate evolution. However, changes in extreme loads which frequently arise from high-wind speeds [56] may well evolve as a result of changing storm intensity and tracking. Wind turbines are designed for different conditions [54] based on hub-height values of the mean annual wind speed, the reference (extreme) wind speed (highest mean 10-min average wind speed value to be expected in a 50-year period) and the characteristic turbulence intensity to be expected at 15 ms^{-1} [51]. Average turbulence levels are most strongly related to site characteristics such as topography and surface type [15] and as such are likely to be only moderately impacted by changes in climate, potential changes in mean wind speeds were discussed above and therefore we limit our discussion below to extreme wind speeds and some of the other principal climatological parameters of interest.

3.1. Extreme wind speeds and gusts

Determining whether the magnitude of the design criteria extreme wind speed (50-year return period 10-min sustained wind speed) will alter in a given location, when and by how much, represents a stringent challenge to climate science. Accordingly, few studies have attempted to examine possible changes in the 50-year return period wind speed [27,57]. Those that been undertaken generally use the Gumbel distribution to represent the probability distribution of extreme wind speeds [58,59]:

$$U_T = \frac{-1}{\alpha}\ln\left[\ln\left(\frac{T}{T-1}\right)\right] + \beta \tag{5}$$

where

U_T wind speed for a given return period (T),
α and β are the distribution parameters.

The distribution parameters (α and β) can be determined via a variety of methods including the method of moments applied to time series of wind speeds, from the method of independent storms, the Weibull parameters [59,60]. The 50-year return period wind speed may be estimated using output from RCM for a time window [27] or the Weibull parameters derived using empirical downscaling transfer functions [61].

Preliminary analyses from both dynamical and empirical downscaling over northern Europe exhibit some evidence for increased magnitude of wind speed extremes [27,57,61,62] (Fig. 2b). The same also appears to be true in analyses for central Europe [63]. These findings are consistent with a tendency towards poleward displacement of storm tracks and fewer but more intense mid-latitude cyclones [29], though caution should be used in interpreting such analyses due to the difficulty in quantifying the occurrence of inherently rare events.

Ten-minute sustained extreme wind speeds are only one component of the wind conditions that can lead to critical loads on wind turbines, others including the extreme of the 3-s average wind speed (or gust) [64–66] and extreme wind direction change [52]. There is currently no method for robustly quantifying the extreme 3-s gust in the context of climate change and thus it can only be treated indirectly by assuming it is embedded within the extreme 10-min sustained wind speed, though new gust parameterizations are being developed and implemented in RCMs [23]. Equally, the authors are not aware of any tools that have been specifically developed to examine extreme wind direction changes in the context of climate change.

3.2. Icing

Icing on wind turbines represents a major challenge to installation and operation of wind turbines in high altitudes and arctic latitudes [67,68]. Wind turbines can be built to withstand extreme conditions and combined wind–diesel systems are an attractive relatively low-cost proposition for remote communities [69]. However, ice accretion on turbine blades can degrade turbine performance and durability [70,71], and even lead to safety concerns associated with ice shedding (if ice is thrown from the rotating blades) [72].

There are two mechanisms of icing. Rime or glaze may form when by what is referred to as the in-cloud processes when supercooled droplets impact on the structure and freeze on contact, or when precipitation freezes after striking the surface [73]. While methods exist to reduce icing (either passive methods such as blade design to reduce ice accumulation, or active methods such as blade heating [70,73,74]), and power production losses due to icing are difficult to unambiguously identify, data from turbines operating in Sweden and Finland indicate that severe icing can lead to turbine stoppages, and even modest accumulation of ice substantially reduces electrical power production, and significantly degrade annual power production [67,68]. Indications are that between 9 and 45% of turbine downtimes in Finland may be attributable to icing events [68].

Few studies have considered these effects in the context of climate evolution. One study over northern Europe calculated icing times using output from a RCM for 1961–1990 vs. 2050–2100 under two SRES (A2 and B2) and using lateral boundary conditions from two GCMs (ECHAM4/OPYC3 and HadAM3). Icing was assumed to occur at the lowest model level when, at that level (90–130 m above ground level), the simulated air temperature was below freezing and the relative humidity exceeded 95%, and was assumed to persist as long as the air temperature remained below freezing after the end of an ice accumulation event. The study resolved substantial declines in the occurrence of icing frequency (of up to 100% in some areas of Scandinavia, depending on the

location and elevation of the site) under all the scenarios considered [75] (Fig. 3). If confirmed these tendencies towards reduced icing frequency may mean sites previously deemed unsuitable for wind turbine deployment due to icing probabilities may become available for development.

3.3. Sea ice and permafrost

At high latitudes, changes in permafrost conditions have a profound impact on road construction and repair which may also influence access for wind farm installation and maintenance [76]. As noted by the Alaska Village Electric Cooperative 'Unfortunately warming trends are affecting the expanse and depth of permafrost. Therefore designing a foundation in the changing permafrost conditions to support all this weight, plus the system frequencies and variable forces exerted by the rotating turbine, is extremely challenging' [77].

Sea ice, and particularly drifting sea ice, potentially greatly enhances turbine foundation loading and thus also represents a critical issue in deployment of wind turbines offshore [78]. Studies of projected changes in sea ice days in the Gulf of Bothnia in the north Baltic Sea indicate a decrease from 130–170 days to 0–90 days in 2071–2100, with many areas becoming ice-free [79]. A study conducted for the entire Baltic Sea indicated large changes in sea ice extent by the middle to end of the twenty-first century under both the A2 and B2 SRES climate change scenarios [75].

3.4. Other factors

Air density affects the energy density in the wind (Eq. (1)) and hence the power output of wind turbines, and is inversely proportional to air temperature, thus increasing air temperature will lead to slight declines in air density and power production. The effect is modest, but not negligible, and at mean sea-level pressure an increase in air temperature of 5 °C (which is within the possible range of changes by the end of the twenty-first century [80]) from 5 to 10 °C leads to a decrease in air density of 1–2% with a commensurate decline in energy density.

Extreme low and high temperatures need to be considered in turbine selection and operation due to their ability to alter the physical properties of component materials (e.g. rubber seals may become brittle at low temperatures), expansion of different materials or determine the necessary fluids for lubrication and hydraulic systems [15]. In northern Europe where the greatest concentration of wind turbines currently is deployed, shifts in the thermal regimes will likely be beneficial in these regards with fewer extremely cold conditions [17]. However, in other regions, warming may cause an increase in the frequency of extreme high temperatures, which may have an impact on the selection of turbine construction materials or lubricants.

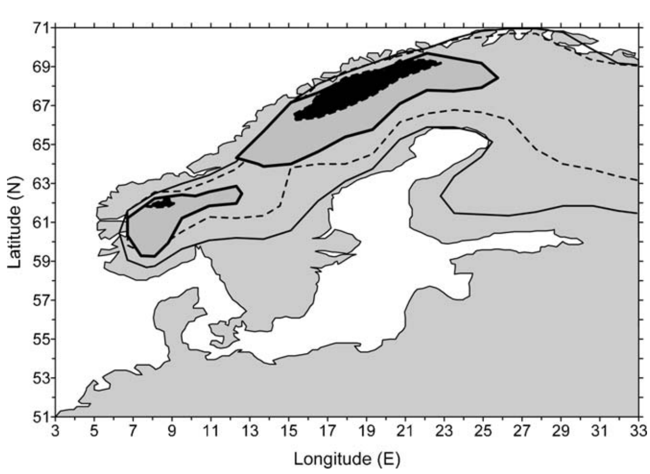

Fig. 3. Number of annual icing hours over northern Europe derived from simulations with the Rossby Centre coupled RCM for 1961–2000 and 2061–2100 (A2 SRES). Lateral boundary conditions were supplied from the ECHAM4/OPYC3 GCM. The solid lines show the isolines bounding 400 and 1200 icing hours per year for the control period (1961–2000), while the dashed isolines depict the same levels but for the 2061–2100 period. The areas enclosed by the 1200 icing hour isolines in the historical and future periods are denoted by the light and dark filled contours, respectively. Figure redrafted from Figs. 7.9 and 7.10 from [75].

Other meteorological drivers of turbine loading such as vertical wind shear, directional distribution and turbulence intensity may also be influenced by climate change but changes in these parameters are difficult to quantify with currently available tools, are likely location specific and likely to be secondary in comparison to changes in resource magnitude, extremes and icing issues.

Changes in land cover/land use (and thus surface roughness length) may impact the future wind resource in some regions (as it has in the historical record [24]), although seasonal variability in surface roughness length were found to have a minor impact on wind resources in one study in northern Europe [81]. It is possible that changes in thermal regimes and the associated mesoscale phenomena (e.g. low-level jets [82] or roll vortices [83]), or changes in inversion height [81] could impact the wind resource and/or wind speed profiles. Coastal flows at higher latitudes are strongly dependent on whether the surface is ice covered or open water [84], and thus may also alter under climate change scenarios but such effects are difficult to quantify and may be local in scale.

Wind turbines are frequently in coastal locations and are being increasing deployed offshore, particularly in Europe [85]. Thus changes in sea-level and/or salinity may also be of importance. Sea level rise largely due to thermal expansion of 4.2 mm/year reported in the 4th Assessment Report of the IPCC [86] may have implications for wind turbines deployed in low-lying coastal areas in terms of foundation loading if flooding becomes more frequent. Corrosion is related to salinity but, if there is general response to global warming, salinity is expected to decrease as the fresh water loading to the oceans increases [87]. There may be local exceptions to this if the balance between run-off and evaporation is altered. Corrosion is also related to humidity and the presence of abrasive particles [15] but the impacts of climate change of these parameters are difficult to assess.

Loading on wind turbines located offshore is a function not only of the wind conditions but also parameters like sea depth and bathymetry which affect wave height and type [88]. The IEC standard 61300-3 has additional requirements for evaluation of external conditions at offshore wind energy sites [89]. The foundation of an offshore wind turbine is subject to the combined action of wind and wave loads, which in turn are a function of the wind speed and significant wave height [15]. Equally the wave state is in turn dictated in part by coupled wind-wave interactions [90], and thus may be modified by changing atmospheric circulation patterns. One study of the northeast Atlantic reported the current 20-year return period wave maybe expected to occur every 4–12 years by 2080 [91]. Downscaling of the mean and extreme wave climate of the North Sea based on wind fields from the HadAM3 and ECHAM4/OPYC3 GCMs suggested most areas would experience an increase in significant wave height of 5–8% by the end of the twenty-first century [92]. In contrast, simulations for the Mediterranean Sea using the WAM model mainly indicated lower significant wave heights under future climate change scenarios [93]. While these changes in wave height in different regions could be consistent with projected poleward shifts in storm tracking across Europe [94,95] it also indicates the large uncertainty in establishing current climates given the large variations on decadal and longer time scales of both wind [42]

and wave heights [96] and the complexity of the processes influencing these parameters.

4. Concluding remarks

Global climate change may change the geographic distribution and/or the inter- and intra-annual variability of the wind resource, or alter other aspects of the external conditions for wind developments. It is likely that as in other components of climate change there will be 'winners' and 'losers' [97]—regions where wind energy developments may benefit from climate change, and regions where the wind energy industry may be negatively impacted. Herein we have provided a very brief synthesis of research being conducted in this arena, highlighted parameters of particular importance and summarized the current state of knowledge.

Global and Regional Climate Models do not fully reproduce contemporary wind climates or historical trends, and empirical and dynamical downscaling studies show large model-to-model variability with respect to the climate change signal. Nevertheless from research conducted to date, it appears unlikely that mean wind speeds and energy density will change by more than the current inter-annual variability (i.e. $\pm 15\%$) over most of Europe and North America during the present century. Some research suggests changes over South America may be of larger magnitude but these estimates are also subject to rather large uncertainty. Only very limited research has been conducted in this field and to determine possible changes in variability across a range of temporal scales, more research is certainly warranted.

Other mechanisms by which climate change may influence the wind energy industry are even less well understood. The 50-year return period wind speed, and probability of icing on wind turbines have implications for turbine design, operation and maintenance, but very few studies have considered these parameters. Preliminary studies from northern and central Europe exhibit some evidence for increased magnitude of wind speed extremes, though changes in the occurrence of inherently rare events are difficult to quantify, and the ability of our downscaling models to reproduce intense and extreme wind speeds has yet to be fully evaluated.

Sea ice, and particularly drifting sea ice, potentially enhances turbine foundation loading and changes in sea ice and/or permafrost conditions may also influence access for wind farm maintenance. One study conducted in northern Europe found substantial declines in the occurrence of both icing frequency and sea ice extent under reasonable climate change scenarios, both of which are physically consistent with expected changes in thermal regimes, and large magnitude warming in high latitudes. However, caution must be exercised in interpreting these results given recognized limitations of RCMs in simulating humidity particularly close to the freezing point of water. Further research in these arenas will help in developing most robust estimates of likely changes.

Other meteorological drivers of turbine loading may also be influenced by climate change but are likely to be secondary in comparison to changes in resource magnitude, extremes and icing issues. Nevertheless it would seem prudent to investigate at least some of these parameters in more detail.

Acknowledgements

The authors acknowledge financial support from the National Science Foundation (grants # 0618364 and 0828655) and Nordic Energy Research (project: Climate and Energy Systems: Risks, potential, adaptation). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] Sims REH, et al. Energy supply. In: Metz B, et al., editors. Climate change 2007: mitigation. Contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007. p. 252–322.
[2] Pimentel D, et al. Renewable energy: current and potential issues. Bioscience 2002;52(12):1111–20.
[3] International Energy Agency I. World energy outlook: 2008. OECD/IEA; 2008. p. 578.
[4] Milford E. American dream? Tackling climate change in the US. Renewable Energy World 2007;36–47.
[5] Dresselhaus MS, Thomas IL. Alternative energy technologies. Nature 2001;414(6861):332–7.
[6] IEA. IEA energy security and climate policy: assessing interactions. Paris, France: International Energy Agency, OECD; 2007 Available from: www.iea.org.
[7] de Vries E. 40,000 MW by 2020: building offshore wind in Europe. Renewable Energy World 2008;36–47.
[8] Milford E. Record growth for wind: what comes next? Renewable Energy World 2008;37–47.
[9] News. 2008 sees wind breaking all records. Renewable Energy World 2009;12(1):10.
[10] de Vries E. The DEWI report: windenergy study 2008. Renewable Energy World 2008;93–101.
[11] Blanco MI. The economics of wind energy. Renewable and Sustainable Energy Reviews 2009;13:1372–82.
[12] European Wind Energy Association. Wind energy. The facts. A guide to the technology, economics and future of wind power. London: Earthscan; 2009 p. 568.
[13] Hubbert MK. Energy resources of the Earth. Scientific American 1971;224:60–70.
[14] Tuller SE, Brett AC. The characteristics of wind velocity that favor the fitting of a Weibull distribution in wind speed analysis. Journal of Climate and Applied Meteorology 1984;23:124–34.
[15] DNV/Risø. Guidelines for the design of wind turbines, 2nd ed., Copenhagen, Denmark: Jydsk cetraltrykkeri; 2002. p. 286.
[16] Mearns LO, et al. NARCCAP, North American Regional Climate Change Assessment Program: a multiple AOGCM and RCM climate scenario project over North America. In: 16th conference on climate variability and change. San Diego: American Meteorological Society; 2005.
[17] Christensen JH, Christensen OB. A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 2007;81:7–30.
[18] ENSEMBLES. Ensemble-based prediction of climate changes and their impacts; 2006. Available from: http://ensembles-eu.metoffice.com/index.html.
[19] Hewitt CD, Goodess CM, Betts RA. Towards probabilistic projections of climate change. Municipal Engineer 2009;162:33–40.
[20] Takle ES, et al. Transferability intercomparison: an opportunity for new insight on the global water cycle and energy budget. Bulletin of the American Meteorological Society 2007;88:375–84.
[21] Hanson C, Goodess CM. Predicting future changes in wind. In: BETWIXT: Built Environment: Weather scenarios for investigation of Impacts and Extremes; 2004.p. 27. Available from: www.cru.uea.ac.uk/cru/projects/betwixt/documents/BETWIXT_TBN_5_v1.pdf.
[22] Goyette S, Brasseur O, Beniston M. Application of a new wind gust parameterization: multiscale case studies performed with the Canadian regional climate model. Journal of Geophysical Research-Atmospheres 2003;108(D13). doi:10.1029/2002jd002646.
[23] Hoglund A, Meier HEM, Broman M, Kriezi E. Validation and correction of regionalised ERA-40 wind fields over the Baltic Sea using the Rossby Centre Atmosphere model RCA3.0. In: Oceanografi. Stockholm: SMHI; 2009. p. 29.
[24] Pryor SC, et al. Wind speed trends over the contiguous USA. Journal of Geophysical Research – Atmospheres 2009; 114 (D14105) doi:10.1029/2008JD011416.
[25] Pryor SC, Barthelmie RJ. Historical trends in near-surface wind speeds. In: Pryor SC, editor. Climate variability, predictability and change in the Midwestern USA. Bloomington, IN: Indiana University Press; 2009. p. 169–83.
[26] Pryor SC, Schoof JT, Barthelmie RJ. Winds of Change? Projections of near-surface winds under climate change scenarios. Geophysical Research Letters 2006;33(L11702). doi: 10.1029/2006GL026000.
[27] Pryor SC, Barthelmie RJ, Kjellström E. Analyses of the potential climate change impact on wind energy resources in northern Europe using output from a Regional Climate Model. Climate Dynamics 2005;25:815–35.
[28] Nakicenovic N, Swart R, editors. Emissions scenarios. 2000. UK: Cambridge University Press; 2000. p. 570.
[29] Christensen JH, et al. Regional climate projections. In: Solomon S, et al., editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.
[30] von Storch H. On the use of "inflation" in statistical downscaling. Journal of Climate 1999;12(12):3505–6.
[31] Pryor SC, Schoof JT, Barthelmie RJ. Empirical downscaling of wind speed probability distributions. Journal of Geophysical Research 2005;110(D19109). doi:10.1029/2005JD005899.
[32] Pryor SC, Schoof JT, Barthelmie RJ. Climate change impacts on wind speeds and wind energy density in northern Europe: results from empirical downscaling of multiple AOGCMs. Climate Research 2005;29:183–98.

[33] Pryor SC, Barthelmie RJ, Schoof JT. Inter-annual variability of wind indices over Europe. Wind Energy 2006;9:27–38.
[34] Bloom A, Kotroni V, Lagouvardos K. Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. Natural Hazards and Earth System Sciences 2008;8(6):1249–57.
[35] Walter A, et al. A high resolution reference data set of German wind velocity 1951–2001 and comparison with regional climate model results. Meteorologische Zeitschrift 2006;15(6):585–96.
[36] Rauthe M, Hense A, Paeth H. A model intercomparison study of climate change-signals in extratropical circulation. International Journal of Climatology 2004;24(5):643–62.
[37] Pryor SC, Barthelmie RJ. Long term trends in near surface flow over the Baltic. International Journal of Climatology 2003;23:271–89.
[38] Breslow PB, Sailor DJ. Vulnerability of wind power resources to climate change in the continental United States. Renewable Energy 2002;27:585–98.
[39] Sailor DJ, Smith M, Hart M. Climate change implications for wind power resources in the Northwest United States. Renewable Energy 2008;2393–406.
[40] Schaeffer R, et al. Climate change: energy security. Universidade Federal do Rio de Janeiro; 2008. p. 145. Available from: www.climaenergia.ppe.ufrj.br/pdf/GCC_ENERGY_SECURITY.pdf.
[41] Garreaud RD, Falvey M. The coastal winds off western subtropical South America in future climate scenarios. International Journal of Climatology 2009;29:543–54.
[42] Pryor SC, Barthelmie RJ, Schoof JT. Inter-annual variability of wind indices across Europe. Wind Energy 2006;9:27–38.
[43] Barthelmie RJ, Murray F, Pryor SC. The economic benefit of short-term forecasting for wind energy in the UK electricity market. Energy Policy 2008;36(5):1687–96.
[44] Olsina F, Roscher M, Larisson C, Garces F. Short-term optimal wind power generation capacity in liberalized electricity markets. Energy Policy 2007;35(2):1257–73.
[45] Frandsen S, Petersen EL. The importance of a good wind year to start on when building a wind farm. In: European wind energy conference 1993; 1993.
[46] Petersen E, Mortensen L, Landberg L, Højstrup J, Frank H. Wind power meteorology. Part I. Climate and turbulence. Wind Energy 1998;1:2–22.
[47] Klink K. Trends and interannual variability of wind speed distributions in Minnesota. Journal of Climate 2002;15:3311–7.
[48] Baker RW, Walker SN, Wade JE. Annual and seasonal-variations in mean wind-speed and wind turbine energy-production. Solar Energy 1990;45(5):285–9.
[49] Milligan MR. Wind plant capacity credit variations: a comparison of results using multiyear actual and simulated wind-speed data. In: Windpower'97; 1997. Available from: http://www.osti.gov/bridge/servlets/purl/629316-j33GqY/webviewable/629316.pdf.
[50] Haralambopoulos DA. Analysis of wind characteristics and potential in the East Mediterranean—The Lesvos Case. Renewable Energy 1995;6(4):445–54.
[51] Hau E. Wind turbines: fundamentals, technologies, application, economics. Birkhäuser; 2006.
[52] Dekker JWM, Pierik JTG. European wind turbine standards II, vol. ECN-C-99-073. Petten: ECN Solar and Wind Energy; 1999.
[53] Frandsen S. Turbulence and turbulence-generated fatigue loading in wind turbine clusters; Risø-R-1188(EN)) available from Risoe National Laboratory, Roskilde, Denmark (and online at; http://www.risoe.dk/rispubl/VEA/veapdf/ris-r-1188.pdf) 2007. p. 128.
[54] IEC. International standard, IEC61400. Part 1. Safety requirements, 3rd edition, IEC, FDIS; 2005.
[55] Veers PS, Butterfield S. Extreme load estimation for wind turbines: issues and opportunities for improved practice. In: AIAA Aerospace Science Meeting; 2001.
[56] Moriarty P. Safety-factor calibration for wind turbine extreme loads. Wind Energy 2008;11:601–12.
[57] Makkonen L, Ruokolainen L, Raisanen J, Tikanmaki M. Regional climate model estimates for changes in Nordic extreme events. Geophysica 2007;43:19–42.
[58] Makkonen L. Problems in the extreme value analysis. Structural Safety 2008;30:405–19.
[59] Cook NJ. The designer's guide to wind loading of building structures. Part 1. Background, damage survey, wind data and structural classification. London: Butterworths; 1986. p. 383.
[60] Palutikof JP, Brabson BB, Lister DH, Adcock ST. A review of methods to calculate extreme wind speeds. Meteorological Applications 1999;6:119–32.
[61] Pryor SC, et al. Climate change impacts on extreme wind speeds. In: proceedings of the Regional Climate Models 2009 conference in Lund, Int. Baltex Secretariat. Publication #41. ISSN 1681-6471; 2009 pp. 271–272.
[62] Haugen JE, Iversen T. Response in extremes of daily precipitation and wind from a downscaled multi-model ensemble of anthropogenic global climate change scenarios. Tellus Series A-Dynamic Meteorology and Oceanography 2008;60(3):411–26.
[63] Leckebusch GC, Weimer A, Pinto JG, Reyers M, Speth P. Extreme wind storms over Europe in present and future climate: a cluster analysis approach. Meteorologische Zeitschrift 2008;17(1):67–82.
[64] Revfeim KJA, Hessell WD. More realistic distributions for extreme wind gusts. Quarterly Journal of the Royal Meteorological Society 1984;110:505–15.
[65] Mitsuta Y, Tsukamoto O. Studies on spatial structure of wind gust. Journal of Applied Meteorology 1989;28(11):1155–60.
[66] Kristensen L, Casanova M, Courtney MS, Troen I. In search of a gust definition. Boundary-Layer Meteorology 1991;55:91–107.
[67] Dalili N, Edrisy A, Carriveau R. A review of surface engineering issues critical to wind turbine performance. Renewable & Sustainable Energy Reviews 2009;13(2):428–38.
[68] Laakso T, et al. State-of-the-art of wind energy in cold climates. Finland: VTT; 2003. p. 53. Available from: http://arcticwind.vtt.fi/reports/state_of_the_art.pdf.
[69] Vasilev VA, Saparov MI, Tarnizhevskii BV. Possibilities of use and promising layouts of power plants employing renewable energy sources in arctic regions of Russia. Power Technology and Engineering 2005;39(5):308–11.
[70] Hochart C, Fortin G, Perron J. Wind turbine performance under icing conditions. Wind Energy 2008;11:319–33.
[71] Frohboese P, Anders A. Effects of icing on wind turbine fatigue loads. In: The science of making torque from wind. Copenhagen: IOP Publishing Journal of Physics: Conference Series; 2007.
[72] IEA. In: IEA wind energy annual report 2007. 2008. p. 286.
[73] Makkonen L, Laakso T, Marjaniemi M, Finstad KJ. Modelling and prevention of ice accretion on wind turbines. Wind Engineering 2001;25(1):3–21.
[74] Maissan JF. Wind power development in sub-arctic conditions with severe rime icing. The Northern Review 2001;24:174–83.
[75] Claussen NE, et al. Wind power. In: Fenger J, editor. Impacts of climate change on renewable energy sources. Copenhagen: Norden; 2007. p. 105–28.
[76] Cheng G. Permafrost studies in the Qinghai–Tibet plateau for road construction. Journal of Cold Regions Engineering 2005;19(1):19–29.
[77] Murphy A. Wind turbine foundations and tower installation. Anchorage: Alaska Village Electric Cooperative; 2008. p. 1.
[78] Mróz A, Holnicki-Szulcb J, Kärnäa T. Mitigation of ice loading on off-shore wind turbines: feasibility study of a semi-active solution. Computers & Structures 2008;86:217–26.
[79] Meier HEM, Doescher R, Halkka A. Simulated distributions of Baltic Sea-ice in warming climate and consequences for the winter habitat of the Baltic ringed seal. Ambio 2004;33:249–56.
[80] IPCC. In: Solomon S, et al., editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom: Cambridge University Press; 2007. p. 996.
[81] Frank HP, Petersen EL, Hyvonen R, Tammelin B. Calculations on the wind climate in Northern Finland: the importance of inversions and roughness variations during the seasons. Wind Energy 1999;2:113–23.
[82] Smedman AS, Hogstrom U, Bergstrom H. Low level jets—a decisive factor for off-shore wind energy siting in the Baltic Sea. Wind Engineering 1996;20(3):137–47.
[83] Etling D, Brown RA. Roll vortices in the planetary boundary layer: a review. Boundary-Layer Meteorology 1993;65:215–48.
[84] Vihma T, Brümmer B. Observations and modelling of the on-ice and off-ice air flow over the Northern Baltic Sea. Boundary-Layer Meteorology 2002;103:1–27.
[85] Barthelmie RJ, Kuhn M. Editoral: preface to special issue on Offshore Wind Energy. Wind Energy 2009;12:103.
[86] Bernstein L, et al. Climate change 2007: synthesis report summary for policy-makers, IPCC AR4 SYR Summary for Policymakers; 2007. p. 23.
[87] Meehl GA, et al. Global climate projections. In: Solomon S, et al., editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.
[88] Bergdahl L, Trumans J, Eskilsson C. Wave loads on wind-power plants in deep and shallow water. In: Wind energy. Berlin, Heidelberg: Springer; 2007. p. 7–13.
[89] Saigal RK, Dolan D, Der Kiureghian A, Camp T, Smith C. Comparison of design guidelines for offshore wind energy systems. In: Offshore technology conference; 2007.
[90] Barthelmie RJ, Bryden I, Coelingh JC, Pryor SC. Energy from the oceans—wind, wave and tidal. In: Sheppard C, editor. Seas at the millennium. Elsevier; 1999.
[91] Wang X, Zwiers F, Swail V. North Atlantic ocean wave climate change scenarios for the twenty first century. Journal of Climate 2004;17:2368–83.
[92] Grabemann I, Weisse R. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. Ocean Dynamics 2008;58:199–212.
[93] Lionello P, Cogo S, Galati MB, Sanna A. The Mediterranean surface wave climate inferred from future climate scenarios. Global and Planetary Change 2008;63:152–61.
[94] Giorgi F, Lionello P. Climate change projections for the Mediterranean region. Global and Planetary Change 2008;63:90–104.
[95] Bengtsson L, Hodges K, Roeckner E. Storm tracks and climate change. Journal of Climate 2006;19:3518–43.
[96] Soomere T. Extreme and decadal variations of the Northern Baltic Sea wave conditions. In: Pelinovsky E, Kharif C, editors. Extreme ocean waves. Springer; 2008. p. 139–58.
[97] O'Brien KL, Leichenko RM. Winners and losers in the context of global change. Annals of the Association of American Geographers 2003;93:89–103.